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SETTLING OF AEROSOL, INTRODUCED INTO THE ATMOSPHERE AS A VERTICAL TURBULENCE STREAM

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13. ABSTRACT

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SETTLING OF AEROSOL, INTRODUCED INTO THE ATMOSPHERE AS A VERTICAL TURBULENCE STREAM

V. F. Dunskiy

A theory of the convective diffusion of an aerosol from a point or a linear source usually considers only the discharge capacity of the source; the remaining properties (initial kinetic and thermal energy etc., imparted to the aerosol) are not considered in the theory.

In the majority of cases such simplification is permissible. However, when solving certain technical problems involving a powerful stream source, this simplification introduces severe distortions, and deprives the results of any practical value.

In solving such problems it is advisable to use the technique of the semi-emperical theory of turbulent streams [1]. An example using this theory is the study of the trajectory of thermal flows in the near-earth layer of the atmosphere [2].

Certain elements of this theory may be also used in solving the problem which we consider here concerning the settling of aerosol from a vertical stream.

When farm crops are sprayed with fine drops using a surface generator which creates a stream of evenly dispersed aerosol (air with drops injected into it) the effective capture width can be considerably increased by directing the stream upward. The stream lifts the drops to a certain height, and the drops settle over a considerably broader area than when the stream is directed horizontally. The height to which the drops of the stream are lifted decreases as the wind speed increases; this decreases the influence from wind velocity on the spread of the drops over the treated area, i.e., the dependence of the results of the treatment on meteorological conditions decreases. These advantages have acted as a stimulus for conducting a series of experiments, (see for example, [3]), in order to confirm the advantages of this method.

The height to which the drops rise is determined by the shape of the stream in the wind carrying it. The shape of the axis of a stream of air flowing into a transverse flow from a circular nozzle can be determined from the following empirical formula, proposed by Shandorov [4]:

$$\frac{x}{2R_0} = \frac{q_{01}}{q_{02}}\left(\frac{z}{2R_0}\right)^{2,55} - \frac{z}{2R_0}\left(1 + \frac{q_{01}}{q_{02}}\right)\operatorname{ctg}\alpha_0, \qquad (1)$$

where x, z - coordinates of the points of the stream axis (the z-axis is directed upward, origin of coordinates lies in the center of the nozzle exit section, x-axis is directed along the drifting flow); R_0, α_0 - nozzle radius and angle formed by the nozzle axis and the drifting flow;

$$q_{01} = \frac{\rho_1 u^2}{2}, \qquad q_{02} = \frac{\rho_2 v_0^2}{2}$$

are the velocity heads in the drifting flow and in the nozzle exit section respectively.

The formula is valid throughout the change of q_{02}/q_{01} from 2 to 22 and α_0 from 45 to 90°.

Yu. V. Ivanov [5] obtained another empirical formula, which is valid in the interval $2 < q_{02}/q_{01} < 1000$, $60° < \alpha_0 < 120°$,

$$\frac{x}{2R_0} = \left(\frac{q_{01}}{q_{02}}\right)^{1,3}\left(\frac{z}{2R_0}\right)^3 + \frac{z}{2R_0}\operatorname{ctg}\alpha_0. \qquad (2)$$

Another theoretical solution to the problem is also known [1], which conforms satisfactorily with formulas (1) and (2).

Exact correspondance between empirical formulas (1), (2) obtained by means of modeling, and a process of interest to us, would have taken place under the condition of geometric similarity and equality of the corresponding criteria of similarity. This condition was not observed; however, the deviations from geometric similarity are of a secondary nature, and the differences in the Reynolds criterion (when Re > 20,000) and in the degree of turbulence of a tangled or a drifting flow has little effect on the structure of the streams ([1], p. 575). Therefore, it may be assumed that formulas (1), (2) may be approximately applied to the considered process of the flow of a vertical turbulent air-drop stream into the atmosphere under conditions which resolve the way in which the spraying is conducted (inversion, isothermy, weak convection).

According to formulas (1), (2), the ordinate of the stream projectory z increases without limit as the distance from the nozzle x increases. However, as the length of the stream increases its average velocity v rapidly decreases (because of the intensive mixing with the surrounding air and the constant momentum), and at a certain $z = \Delta H$ the vertical component v_z of the average stream velocity approaches in magnitude the vertical component u_z^1 of the average pulsating velocity of the

drifting flow, after which the difference between the stream and the drifting flow for all practical purposes disappears. It may be shown that the statement $v_z = u_z^1$ approximately corresponds to the inclination of the stream $\mathrm{tg}\ \alpha = 0.2$, whence, from formula (2) we obtain the following formula for the height to which the stream is lifted (i.e., rise of the particles under the generator nozzle);

$$\Delta H = 2{,}58 R_0 \left(\frac{v_0}{u}\right)^{1{,}3}. \qquad (3)$$

The corresponding $\Delta x = 1.66\ \Delta H$. Since the width of the area over which the drops settle exceeds H by tens of times (see below), the quantity Δx can be neglected during the computations.

At a rate of gravitational settling of the particles $w \gg u_z^1$, i.e., for the most uneven aerosol, the true height to which the particles are lifted can turn out to be less than that computed according to formula (3); such particles fall from the stream in the direct vicinity of the generator with the appropriate generator construction and proper selection of the operating conditions. These particles make up an insignificant portion of the sprayed substance.

After determining the effective height of the source $H = H_1 + \Delta H$ (H_1 - height of the initial section of the stream above the ground), the settling of the mixture on the ground can be computed by using the theory of atmospheric diffusion. The problem is formulated as follows: a continuous point source[1] of the (settling) mixture moves to height H with constant speed v_n perpendicularly to the wind, and moves over path l in time T. We seek the solution to the equation of unsteady diffusion under the corresponding initial and boundary conditions.

[1]An element of an aerosol stream at height H may be approximately considered as a point source, since the dimensions of the stream cross section at this height are small in comparison with H.

With such a formulation of the problem its solution is complex, and it is difficult to obtain simple computational formulas; further simplifications are advisable.

Let us show that considerable simplifications are possible without damaging the accuracy of the solution if we limit ourselves to determination of the density of the deposit of mixture on the ground. The considered process is unsteady: local values of the concentration of mixture $c(x, y, z, \tau)$, in the near-earth layer of air are time-variable. However, the accumulated values $\int_0^\infty c(x, y, z, \tau)d\tau = \phi(x, y, z)$, obtained by summing the instantaneous values of c at each point, and determining the density of the deposit of mixture on the ground, possess a stationary (time-independent) field. In solving this problem, as in the majority of problems related to the deposit of a heavy mixture of the near-earth layer of air to the ground, we are usually interested in the density of the deposit of mixture, i.e., the accumulated, and not the instantaneous values of the concentration. Therefore the nonstationary problem of the deposit of mixture from an instantaneous continuous moving source may be reduced to the stationary problem of the deposit of mixture from an equivalent[1] continuous fixed source.

We will prove the admissibility of such a simplification for the most simple case of an instantaneous point source, namely, that from the point of view of deposits being formed, it can be replaced by a continuous point source, equivalent in power.

Assume to be known the function $G_1 f(x, y, z, \tau - t)$, determining the fields of concentrations c for an instantaneous point source with output G_1 kg, operating at $\tau = t$. The density of

[1]In the sense of created deposits.

the deposits of mixture of the ground ($z = z_0$), created by this source at a rate of gravitational settling of particles w,

$$g_1 = G_1 w \int_t^{\infty} f(x, y, z_0, \tau - t)\, d\tau,$$

or, after transforming the variable under the integral sign $\tau = \theta + t$, and the corresponding change of the limits of integration

$$g_1 = G_1 w \int_0^{\infty} f(x, y, z_0, \theta)\, d\theta. \qquad (4)$$

Let us now turn to a continuous point source with output G_2 kg/s.

Using the principle of superposition, we will consider it as the totality of an infinitely large number of elementary instantaneous point sources with output $G_2 d\tau$, operating in series over an infinite fraction of time τ. Field of concentration dc, created by each source at time $\tau = t$

$$dc = G_2 d\tau f(x, y, z, t - \tau).$$

The total concentration of mixture created by the totality of elementary sources at a time $\tau = t$

$$c = G_2 \int_{-\infty}^{t} f(x, y, z, t - \tau)\, d\tau = G_2 \int_{t}^{-\infty} f(x, y, z, t - \tau)\, d(-\tau).$$

or after transforming the variable under the integral sign, $\tau = t - \theta$, and the corresponding change of the limits of integration

$$c = G_2 \int_0^{\infty} f(x, y, z, \theta)\, d\theta.$$

The density of the deposit left after one second by the totality of elementary sources, corresponding to the continuous source under consideration,

$$g_2 = cw = G_2 w \int_0^{\infty} f(x, y, z_0, \theta)\, d\theta. \qquad (5)$$

With identical flow rates of mixture, i.e., when G_1[kg] = G_2[kg/s], expressions (4) and (5) are identical, and $g_1 = g_2$; the equivalence has been proved.

An analogous method may also be used to prove the equivalence (in our sense) of both instantaneous and continuous linear sources of infinite extent, instantaneous and continuous linear of finite length etc. We can also prove the equivalence of sources as applied to our problem, namely, a continuous linear source of length l, passing over path l in time T. Neglecting boundary effects, the latter can be approximated by a source of infinite extent.

As a result of our simplification the problem reduces to the solution of the equation of steady diffusion

$$u(z)\frac{\partial c(x, z)}{\partial x} - w\frac{\partial c(x, z)}{\partial z} = \frac{\partial}{\partial z}\left[K(z)\frac{\partial c(x, z)}{\partial z}\right] \qquad (6)$$

as applied to the settling of an evenly dispersed aerosol on the vegetation cover of the earth, i.e., taking into consideration not only settling due to gravity, but also settling due to inertia. As was shown in [6], in this case the boundary conditions on the upper edge of the vegetation cover z = h

$$\frac{\partial c(x, h)}{\partial z} = aC(x, h), \qquad (7)$$

where

$$a = \frac{h\alpha\beta u(h) + w(h\beta_r - 1 + \xi)}{K(h)}, \qquad (8)$$

$\xi = \frac{c(xo)}{c(xh)}$; α - coefficient for the retention of particles by plants; β - specific area of projection of plants onto an area normal to $\vec{u}$; β_r - specific area of horizontal projection of plants; K - coefficient of convective diffusion.

The condition of the source

$$c(0, z) = \frac{G}{u(H)}\delta(z - H),$$

where δ - delta-function symbol; G - output of continuous linear source, $\frac{kg}{m \cdot s}$.

The condition on infinity

$$c \to 0 \quad \text{when} \quad \sqrt{x^2 + z^2} \to \infty.$$

The solution to this problem when

$$K(z) = kz, \quad u(z) = u_0 z^q,$$

(which corresponds to isothermy), is given in [6], u_* - "speed of friction," z_0 - roughness factor. In addition to precise solution there is an approximate formula for the density of deposit of mixture of the ground

$$g_0 = \frac{\xi w c_0 (x, 0)}{2\beta h u (h)/w + \xi}, \tag{9}$$

where

$$c_0(x, 0) = \frac{G(1+q)}{Hu(H)} \frac{\exp(-A/x)}{\Gamma(1-p)} \left(\frac{x}{A}\right)^{p-1}, \tag{10}$$

This is the solution of Rounds [7] for z = 0 in the same problem, but without taking into consideration settling due to inertia; in place of condition (7) we have

$$K(z) \frac{\partial c(x, z)}{\partial z} \to 0 \quad \text{as} \quad z \to 0.$$

Here Γ is the gamma-function symbol

$$A = \frac{Hu(H)}{0{,}4(1+q^2)u_*}, \quad p = -\frac{w}{0{,}4u_*(1+q)},$$

u_* - "feed of friction."

Let us now compare the results of computations according to formulas (9) and (10) with the experimantal data.

An experimental study of the settling of an aerosol from a vertical turbulent stream created by a moving generator was

conducted in the Krasnodarsk Kray and the Armenian SSR [8] and in the Kustanay oblast [3]. The experiments [8] were conducted with aerosol generators EAU-1 and AG-L6, equipped with an angled Venturi tube; the liquid was sprayed by a high-speed air flow in a narrow section of the tube. The output and the power of the stream were approximately identical for both generators. The experiments in [3] made use of a significantly higher-power generator OPS-30, equipped with an angled tube having large through sections. The long-range vertical stream created by this generator ensures up to 200 m coverage span.

During the experiments, the generator, placed on a two-wheel trailer or on the platform of a truck, moves perpendicularly to the wind at a speed of 4-6 kg/h. Vessels and glasses are spread around on the ground parallel to the wind in order to measure the amount of liquid which has settled on the ground under the plants, and the dimensions of these drops.

The glasses had been preliminarily coated with a layer of zinc stearate or silicone in order to ensure a constant contact angle (spreading factor) of drops of different dimensions. The glasses with the deposited drops were examined under a microscope; the drops were counted and measured, then divided into classes by dimensions taking into consideration the area of glass which was examined. Preliminary experiments had established that the effect of evaporation of drops of the volatile liquids which had been used (transformer oil and solar oil) could be neglected.

In comparison with theory the generator of polydisperse aerosol was considered as the totality of several sources of monodisperse aerosol (fractions with narrow range of drop dimensions) acting independently; the settling of each fraction was analyzed separately.

The degree of dispersion of the aerosol in the stream at the generator exit was determined with the use of a cascade impactor with slot-type gate. The output of the source, corresponding to the i-th fraction of aerosol, was taken as $G_i = Gh_i$, where h_i is the relative weight of the i-th fraction at the generator exit.

During each experiment gradient measurements were made of the average wind velocity u and air temperature t at 0.5 and 2 m. According to the results of the gradient measurements in the isothermic state, the roughness factor z_0 was determined.

The experiments were carried out over smooth areas, covered with a sparse grass 5-15 cm high (plain, virgin soil).

In order to decrease the effect of fluctuations in the density of aerosol deposit g it is advisable to use for comparison the averaged results of several experiments, conducted under approximately identical meteorological conditions, or conducted with a double treatment when the fluctuations are less. The conditions of conducting these experiments are given in Table 1.

The values of the density of deposit g_0 of the individual fractions of aerosol, averaged for each group of experiments, was taken for comparison; during the computations the values of parameters given in Table 2 were used.

It is not difficult to see that the small $\alpha\beta h$ values make the denominator in the right side of formula (9) close to unity, i.e., under the given conditions (low sparse grass, 100-μ drops) the settling due to inertia plays a secondary role.

Figure 1 compares the results of the computations (solid lines) and experiments (points) for one of the aerosol fractions

Table 1

No. experiment	Time of beginning experiment, h, min.	Site of experiment	Generator	Liquid	Height above ground of exit section of tube, m.	Radius of exit section of tube, m.	Rate of discharge of aerosol, m/s.	Flow rate of liquid kg/min	Wind velocity m/s		Air temperature difference $t_{0.5}-t_{2.0}$
									0,5	2,0	
1	6 42	Krasnodarsk Kray	EAU-1 with angle tube	Transformer oil	1,70	0,04	32	3,26	2,[illegible]	3,0	− 0,07
2	6 12	"	"	"	1,70	0,04	32	3,21	2,3	3,0	+0,1
3	6 12	"	"	"	1,70	0,01	32	3,02	2,2	2,9	+0,[illegible]
4	14 16	"	"	"	1,70	0,01	32	3,16	2,2	2,9	+0,12
5	16 10	[illegible]	[illegible]-16 with angled tube	Solar oil	1,80	0,022	73	3,05	4,5	6,3	+1,[illegible]
6	16 38	"	"	"	1,80	0,022	73	3,15	5,1	7,0	+2,1
7	19 47	"	"	"	1,80	0,022	73	2,9[illegible]	3,3	3,7	+0,[illegible]
8	19 05	Kustanay Oblast	[illegible]-30 with angled tube (double treatment)	"	2,8	0,1	41	13,[illegible]	3,4	4,3	−0,0[illegible]

Table 2. Fraction d = 90-120 μ.

[illegible]	θ^1	w m/s	h^1 m	$\alpha\beta h^1$	$u(h)$ m/s	G g/s	ζ	H m	z_0 m	u^1 m/s	q'	$u(H)$ m/s
1, 2, 3, 4	1,0	0,214	0,05	0,0015	1,5	69,5	0,144	3,80	0,0052	0,199	0,176	3,3
5, 6, 7	1,0	0,214	0,05	0,0015	2,8	61	0,248	3,07	0,0013	0,42	0,213	6,7
8	1,0	0,214	0,08	0,006	2,8	257	0,310	6,60	0,0066	0,30	0,150	5,4

[1] See [6]

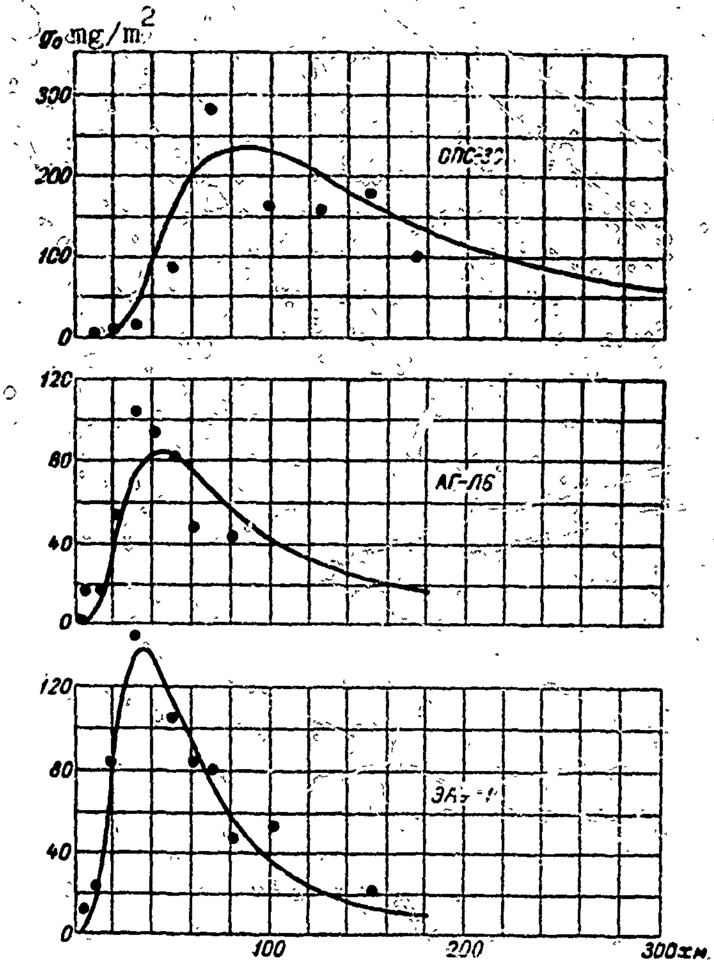

Fig. 1. Computed and measured values of density deposits g_0 of drops with diameter 8-114 μ in a stream of aerosol directed upward.

for three different generators. The agreement between the measured and the computed values of g_0 is satisfacotry. Analogous results were also obtained for the other fractions.

Thus, our method (using the theory of convective diffusion with the theory of turbulent streams) gives us results which agree satisfactorily with experimental data, and lead to formulas which are suitable for approximate practical calculations.

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